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# Chromatic adaptation under diverse illumination conditions

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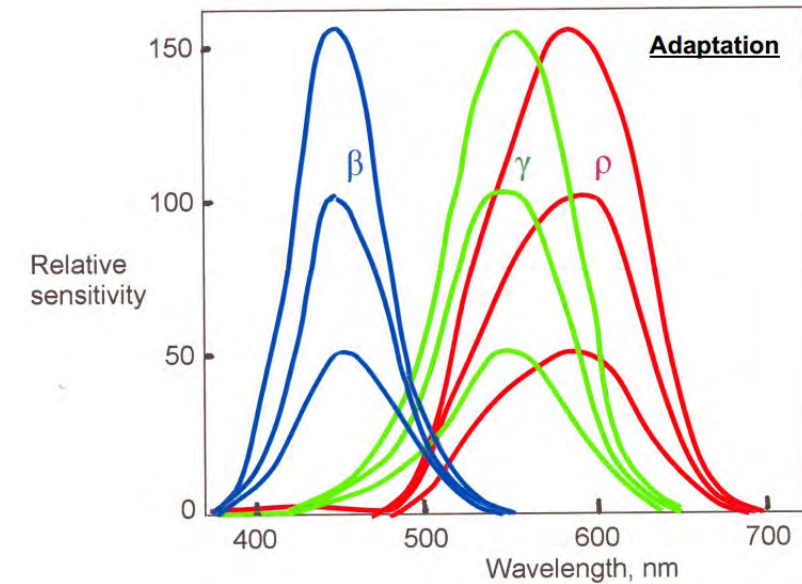
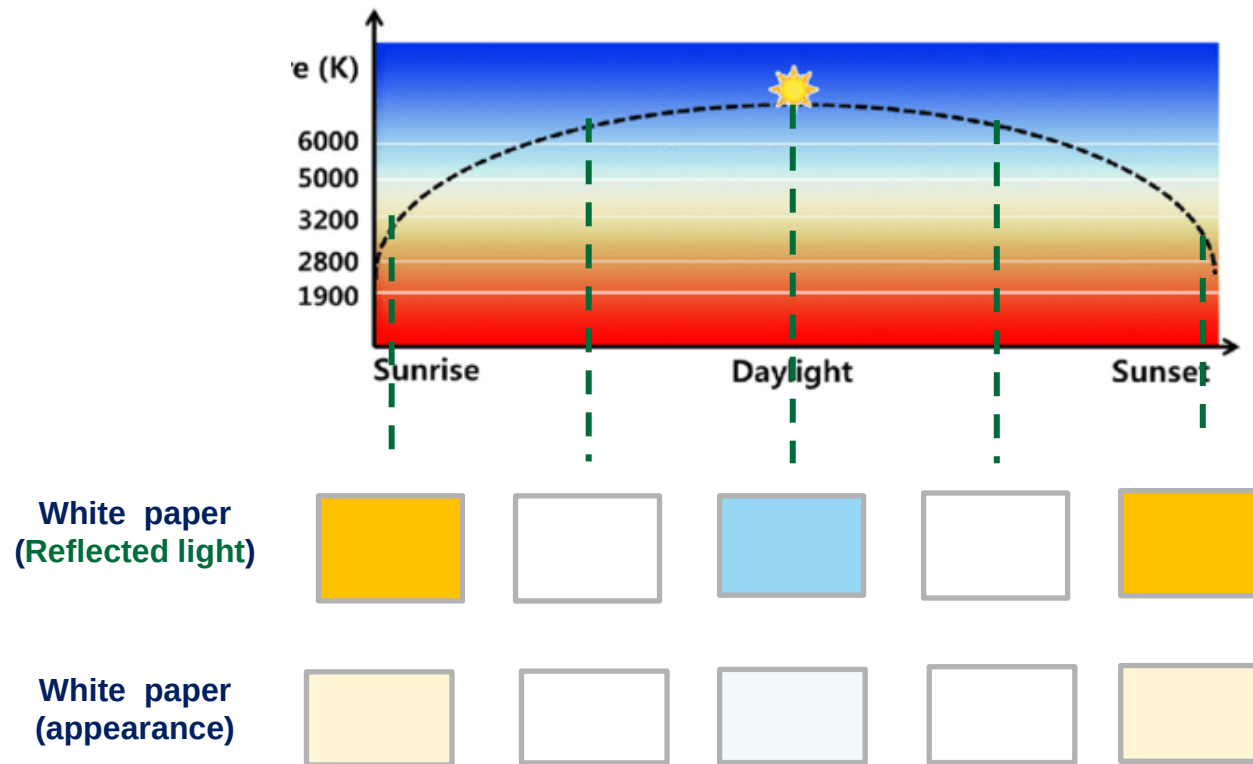
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Part 01

# Introduction

Natural daylight (CCT): 2000 ~ 25000 K



- Sensitivity of each cone type is adjusted relative to the incident light
- The shape of the spectral sensitivity curve keeps consistent

## Chromatic adaptation:

The ability of the **visual system** to **adapt to the background** (color) and keep the color appearance of objects **constant** across changes in illumination color

## ■ Application of chromatic adaptation

**Aim:** Ensure consistent color appearance of stimulus under varying illuminations

**Application:** color reproduction, white balance.....

Display



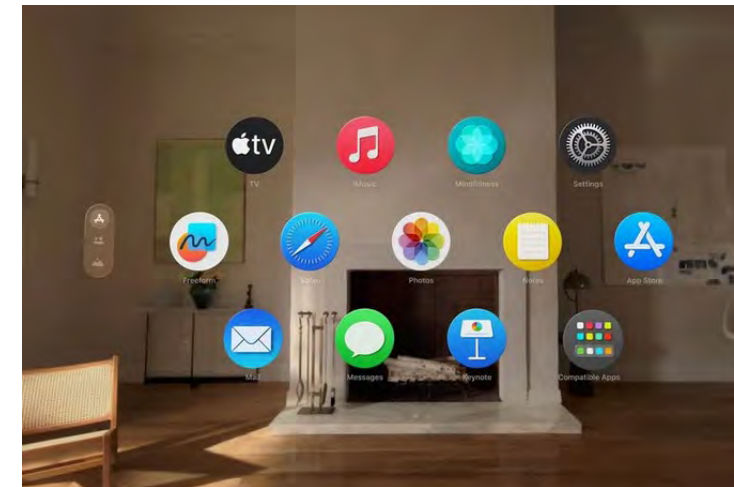
- Self-luminous stimulus
- Unrelated color, irrelevant to viewing surrounds

Real scene



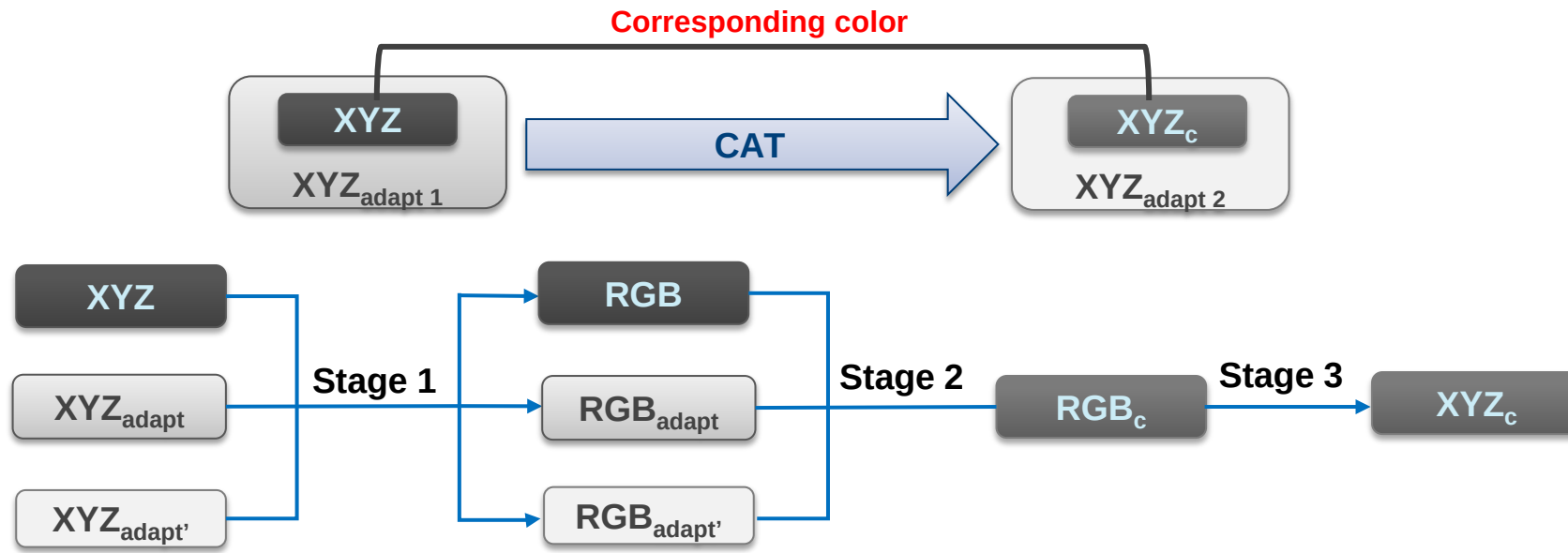
- Related color
- Correlated with surrounds under varying illuminations

Augmented reality



- Optical see-through, overlay digital content onto real world
- Partially affected by background

- Chromatic adaptation transform (CAT)



- The structure of von Kries CAT:

$$\begin{pmatrix} L_c \\ M_c \\ S_c \end{pmatrix} = \left[ D \begin{pmatrix} L_{rw} / L_w \\ M_{rw} / M_w \\ S_{rw} / S_w \end{pmatrix} + 1 - D \right] \begin{pmatrix} L \\ M \\ S \end{pmatrix}$$

$L, M, S$ : cone signals

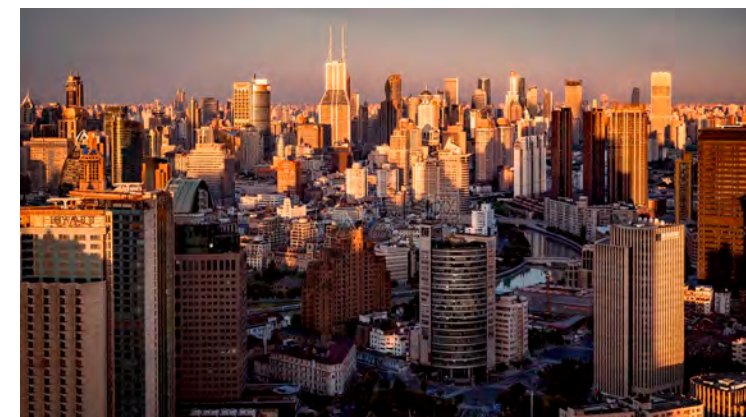
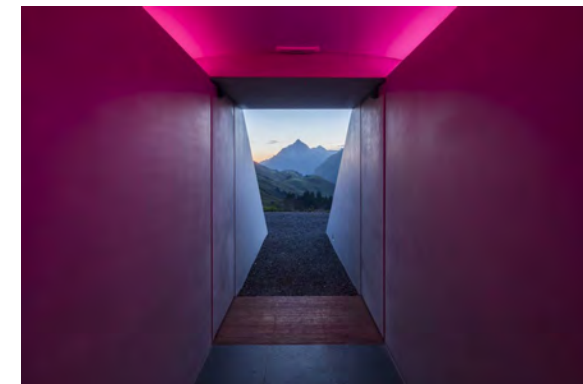
$D$ : degree of adaptation (0 ~ 1)

$$\text{CIECAT02: } D = F \left[ 1 - \left( \frac{1}{3.6} \right) \exp \left( \frac{-L_a - 42}{92} \right) \right]$$

## ■ Corresponding color datasets

| Dataset    | Experiment method | No. of observer | Viewing medium             | Sample        |                             | Illuminant        |                        |                             |
|------------|-------------------|-----------------|----------------------------|---------------|-----------------------------|-------------------|------------------------|-----------------------------|
|            |                   |                 |                            | No. of sample | The type of the test sample | Test illumination | Reference illumination | Luminance of adapting field |
| CSAJ-C     | Haploscopic       | 104             | Lighting booth             | 87            | Color chips                 | A                 | D65                    | 318                         |
| Kuo & Luo  | Magnitude         | 5               | Lighting booth             | 40~41         | Wool samples                | A, TL84           | D65                    | 340~730                     |
| Lam & Rigg | Memory            | 5               | Lighting booth             | 58            | Wool samples                | A                 | D65                    | 320~370                     |
| Helson     | Memory            | 6               | Lighting booth             | 59            | Munsell samples             | A                 | C                      | 195~250                     |
| LUTCHI     | Magnitude         | 6 or 7          | Lighting booth             | 41~44         | OSA uniform color scale     | A, D50, WF        | D65                    | 232~252                     |
| Breneman-C | Haploscopic       | 7 or 8          | Transparent photograph     | 12            | Bipartite mirror            | A, Y, G           | D55, D65               | 15~11100                    |
| Fairchild  | Matching          | 5               | Lighting booth and display | 16~17         | Objects on the image        | D30, D93          | D65                    | 41                          |
| McCann     | Haploscopic       | 15              | Projector                  | 68            | Mondrian area               | R, G, B, Y        | D65                    | 14 ~ 40                     |

- Existing CATs:
  - o RLAB, CMCCCAT97, CMCCAT2000, CIECAT02, CAT16...
- Limitations:
  - o Derived from data sources with **uniform, near neutral** test illuminants
  - o The degree of adaptation only depends on the **adapting luminance** (except RLAB)
  - o Adaptation state under dichromatic illumination is unknown
- Aim:
  - o Investigate various factors related to illumination and stimulus on adaptation state
  - o Develop a comprehensive model that can predict corresponding colors under uniform and dichromatic illuminations

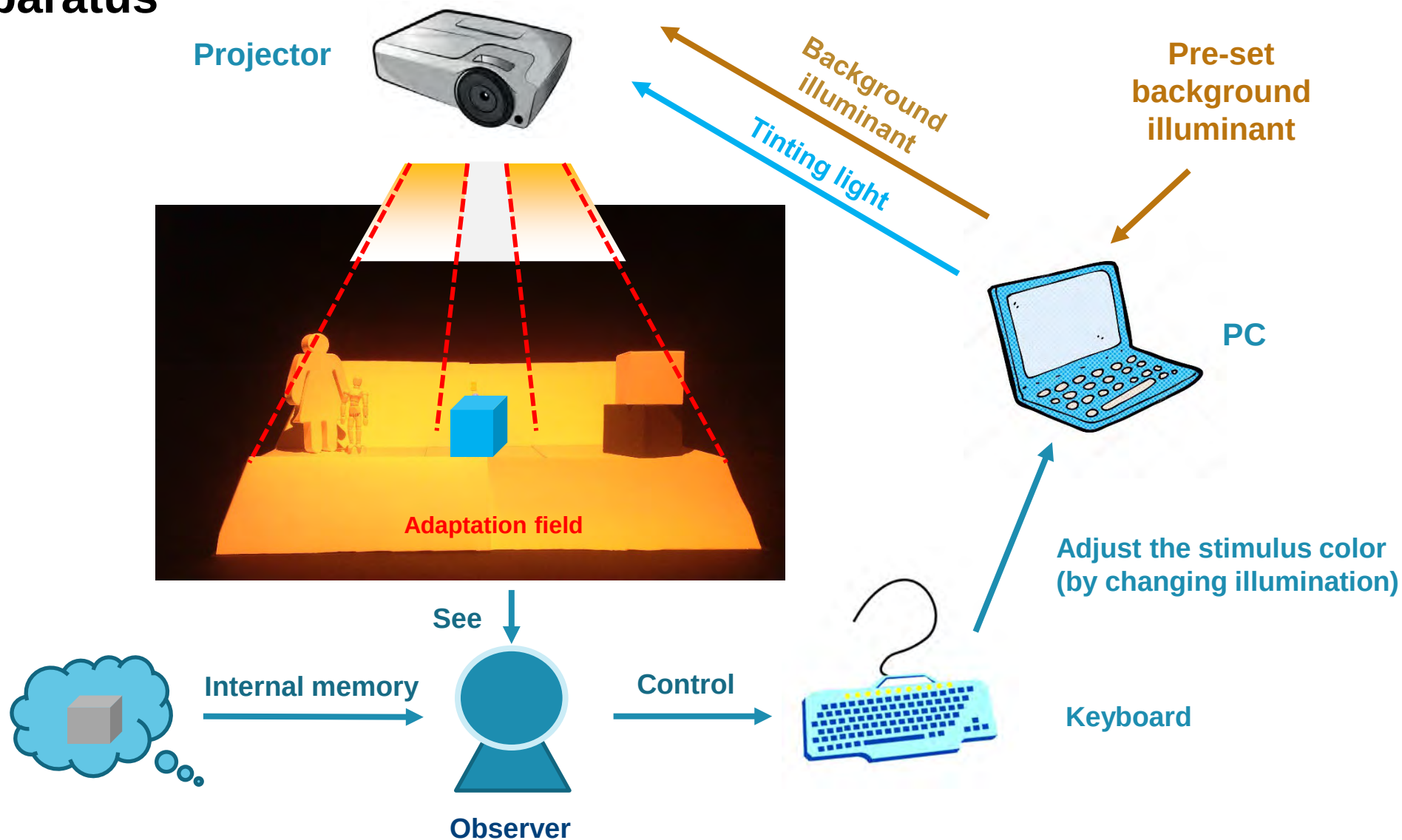




Part 02

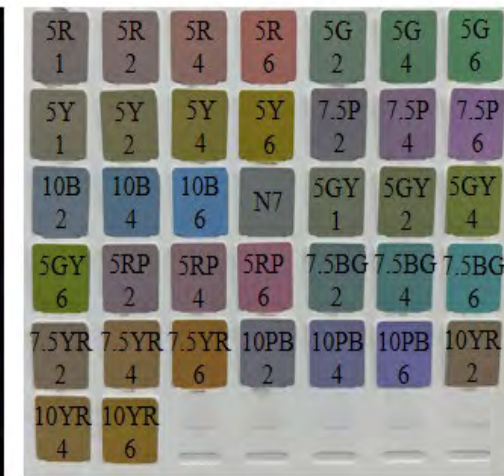
# Single illumination

## ■ 2.1 Apparatus



## 2.2 Color stimuli

- **Illumination: Eight colors**
- **Experiment method:**
  - Achromatic matching (two media)
  - Neutrality rating (three media)
- **Viewing media:**
  - Self-luminous display
  - Surface color (Munsell sample)
  - Independently illuminated surface color
- **10 participants**



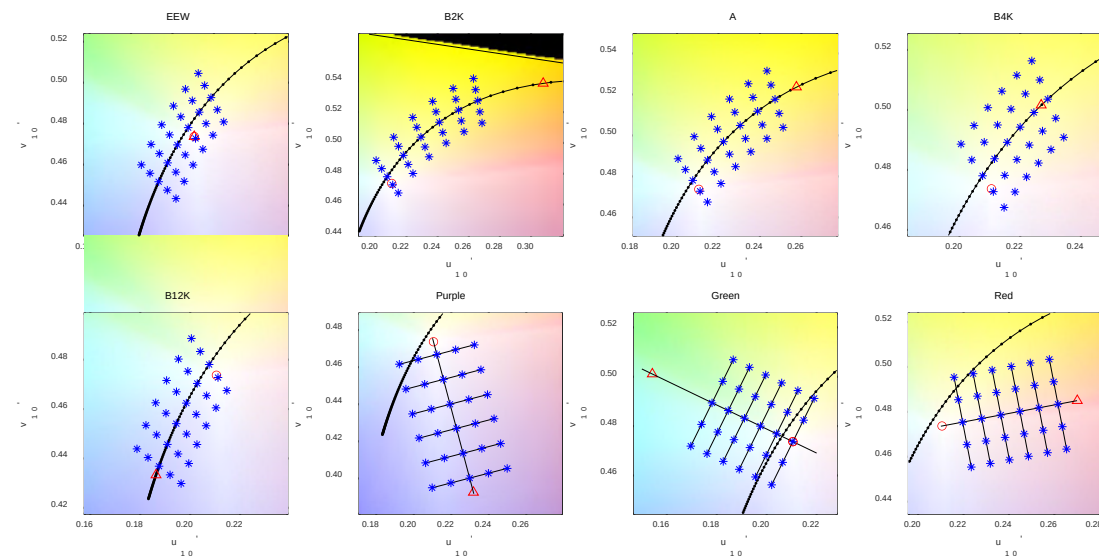
Projected sample



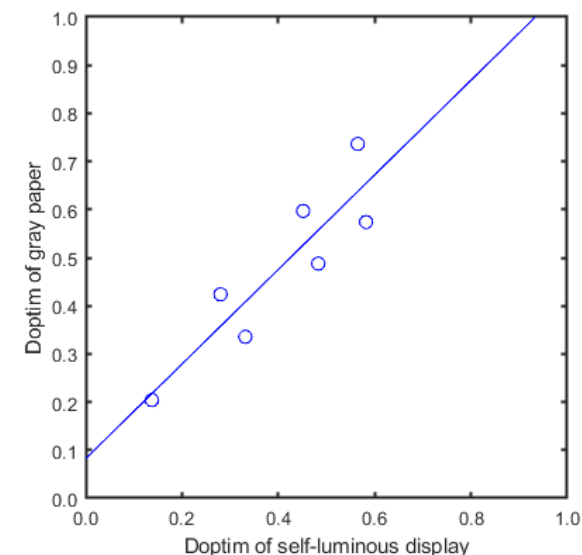
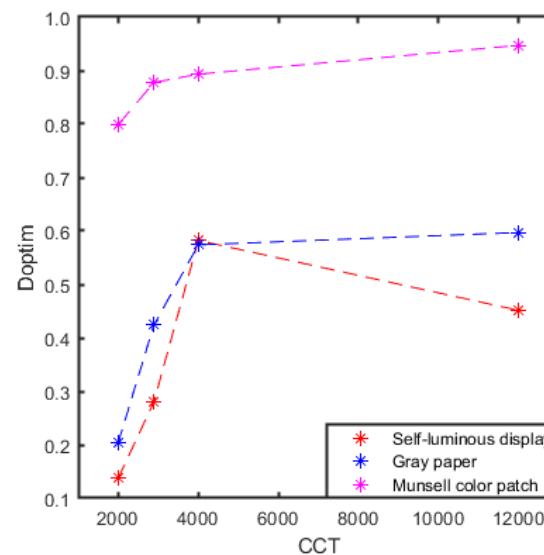
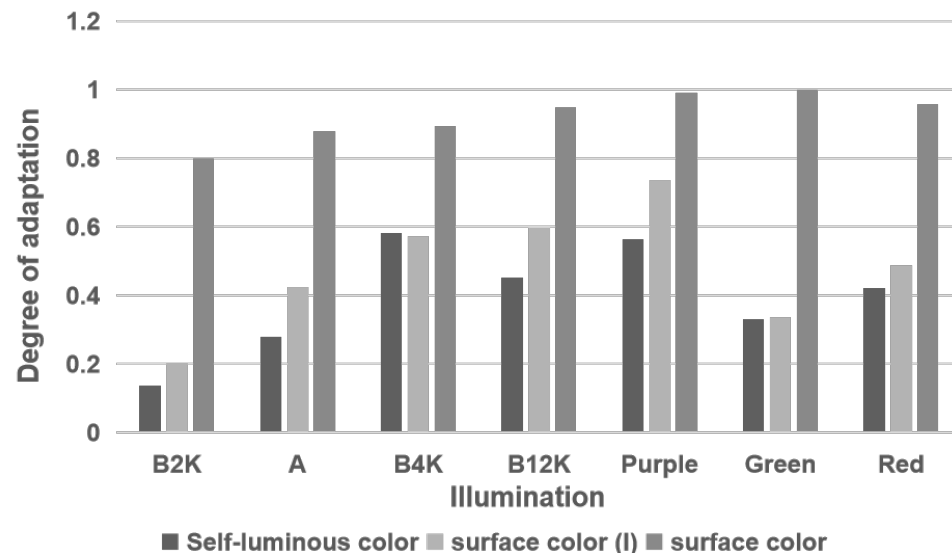
Display



Surface color



## 2.3 Adaptation state comparison



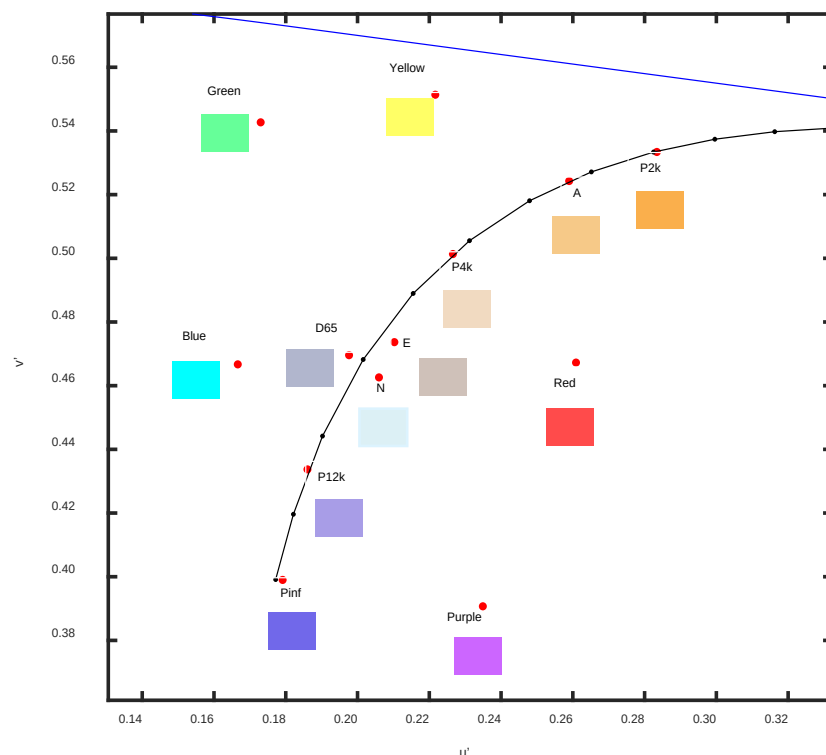
- Adaptation state varies with illumination color: lowest for the low-CCT illumination
- Self-luminous display exhibits the lowest  $D$ , while surface color has the highest  $D$  (near complete)
- Even though the color of projected stimulus is unaffected by illumination, it exhibits a higher  $D$  than display (Probably due to the rich surface texture information)
- For self-luminous and projected stimuli, the degree of adaptation is more sensitive to illumination color

## ■ 2.4 Performance comparison

| Model                         | Self-luminous color |                   | Independently illuminated surface color |                   | Surface color     |
|-------------------------------|---------------------|-------------------|-----------------------------------------|-------------------|-------------------|
|                               | Achromatic matching | Neutrality rating | Achromatic matching                     | Neutrality rating | Neutrality rating |
| $D_{CAT02}$                   | 0.039               | 0.033             | 0.029                                   | 0.025             | 0.008             |
| $D_{optim}$<br>(Ground truth) | 0.007               | 0.005             | 0.008                                   | 0.006             | 0.003             |
| $D_{Ma}$                      | 0.018               | 0.013             | 0.011                                   | 0.009             | 0.023             |
| $D_{Zhai}$                    | 0.020               | 0.015             | 0.014                                   | 0.012             | 0.003             |
| $D_{CAT16}$                   | 0.036               | 0.030             | 0.026                                   | 0.023             | 0.008             |

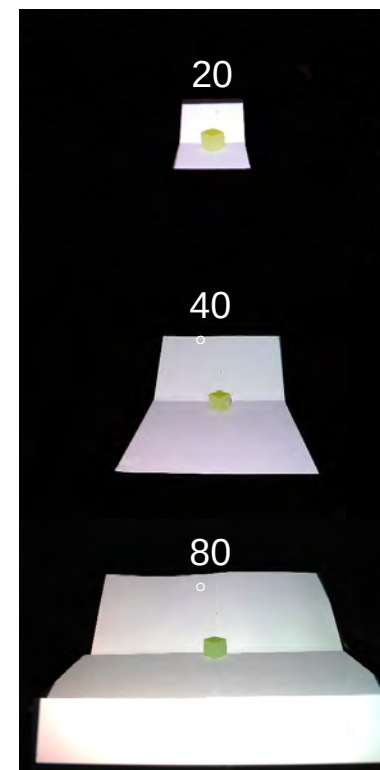
## 2.5 Experimental details

Illumination chromaticity

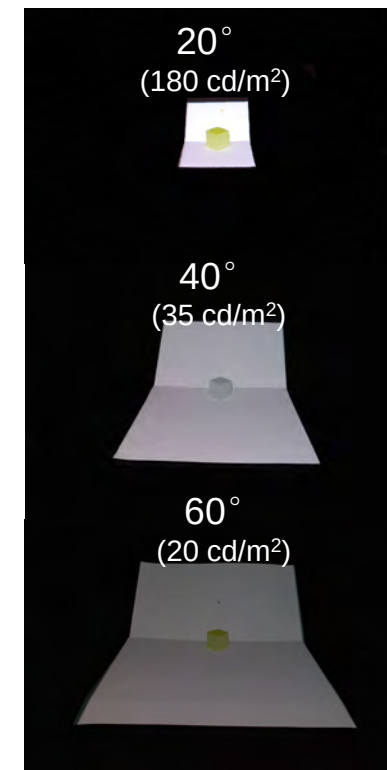


### Adapting field size

EL group  
(180 cd/m<sup>2</sup>)

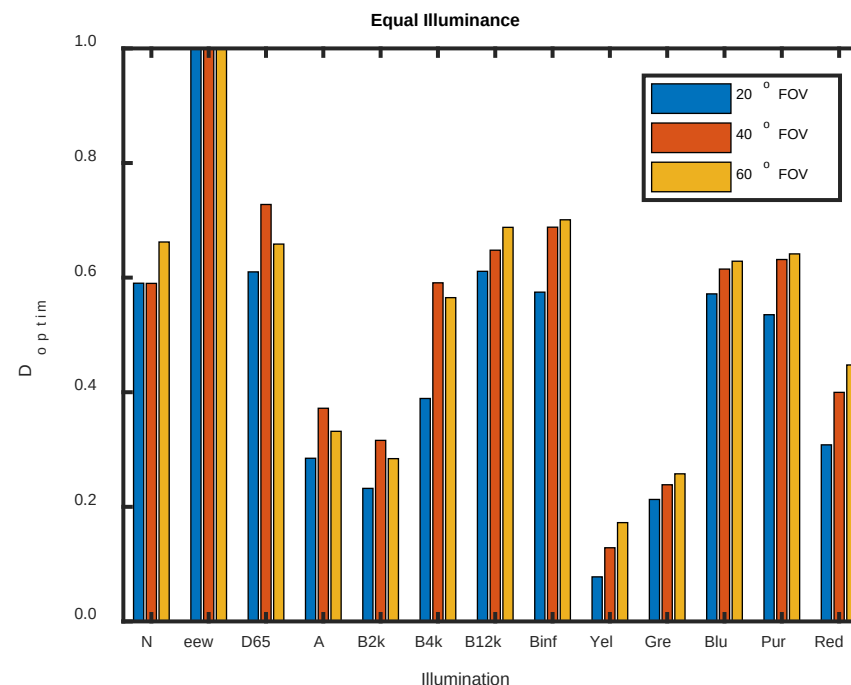
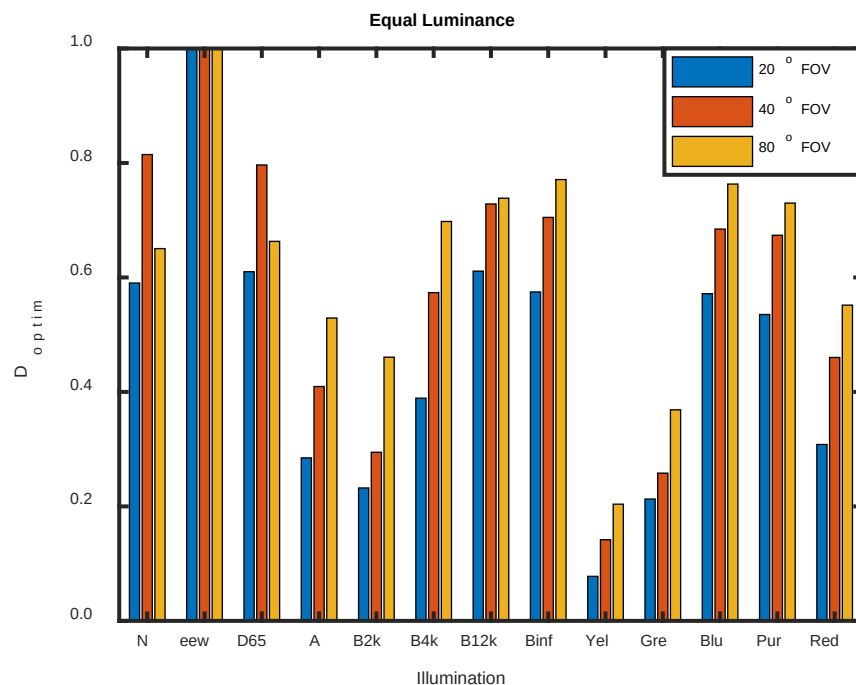


EI group  
(7 lx)



- Equal luminance (180 cd/m<sup>2</sup>): 20°, 40°, 80°
- Equal illuminance (7 lx): 20°, 40°, 60°

## 2.6 Degree of adaptation (D)



Larger field of view → Larger degree of adaptation

$$D(20^\circ) < D(40^\circ) \approx D(60^\circ)$$

Higher chroma

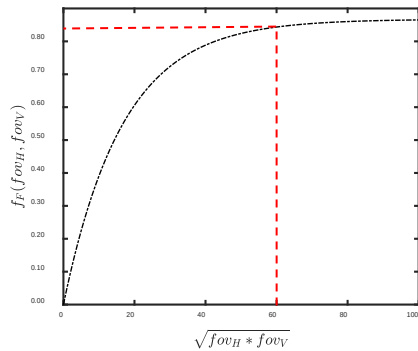


Lower degree of adaptation  
(especially for yellowish illuminants)

## 2.7 New model

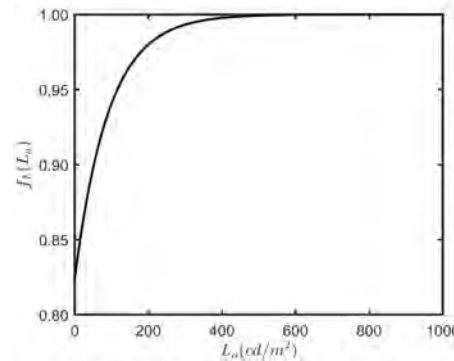
$$D_{Ma} = f_F(fov_H, fov_V) \times f_L(L_a) \times f_{Chroma}(u'_{F,10}, v'_{F,10})$$

Size factor



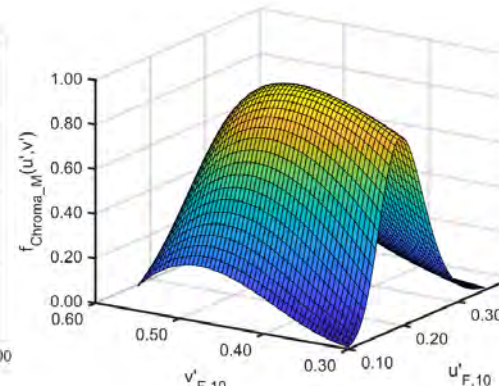
Saturate at 60°

Luminance factor

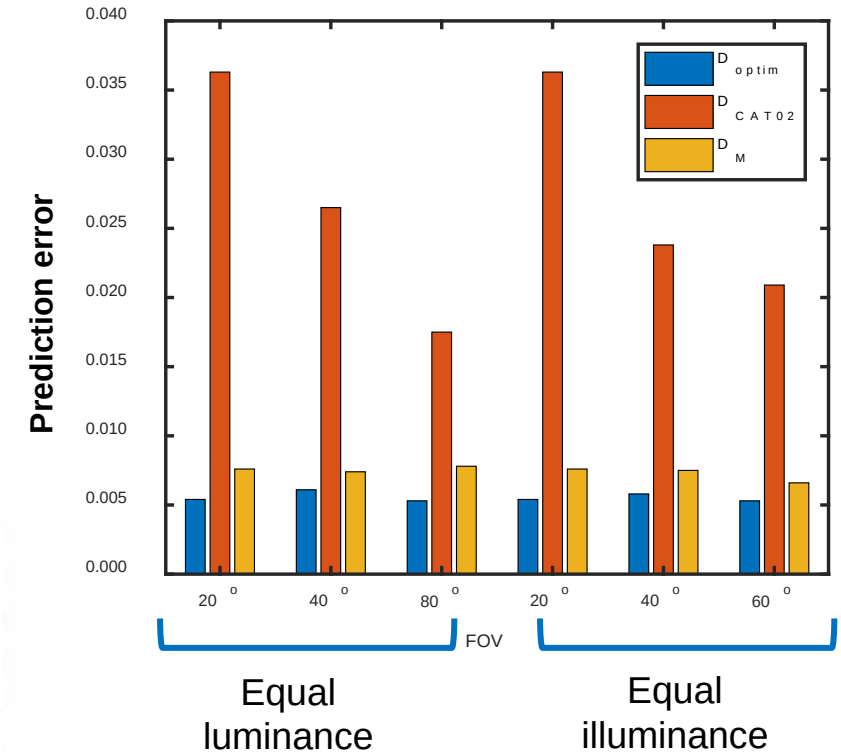


Saturate at 400 cd/m<sup>2</sup>

Chromaticity factor



Bivariate Gaussian



### Performance:

$$D_{optim} > D_M \gg D_{CAT02}$$



Part 03

# Complex illumination

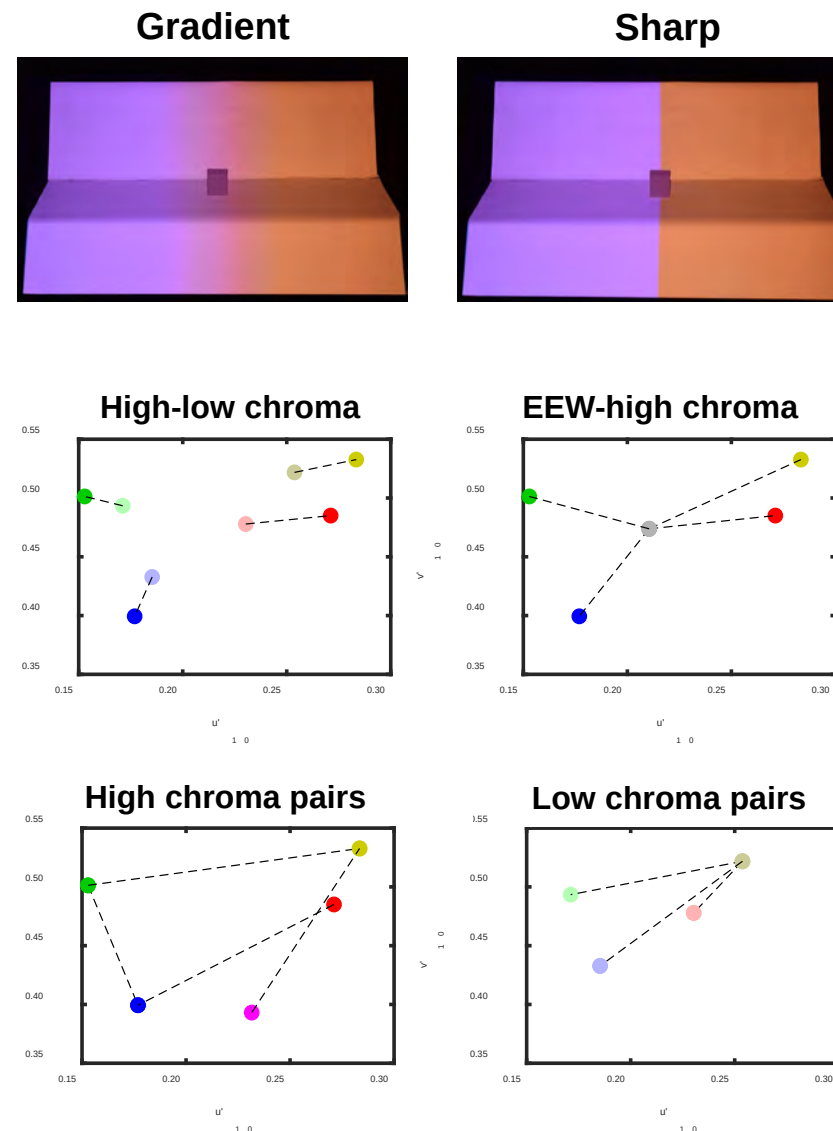
## ■ 3.1 Backgrounds

### • Illumination conditions

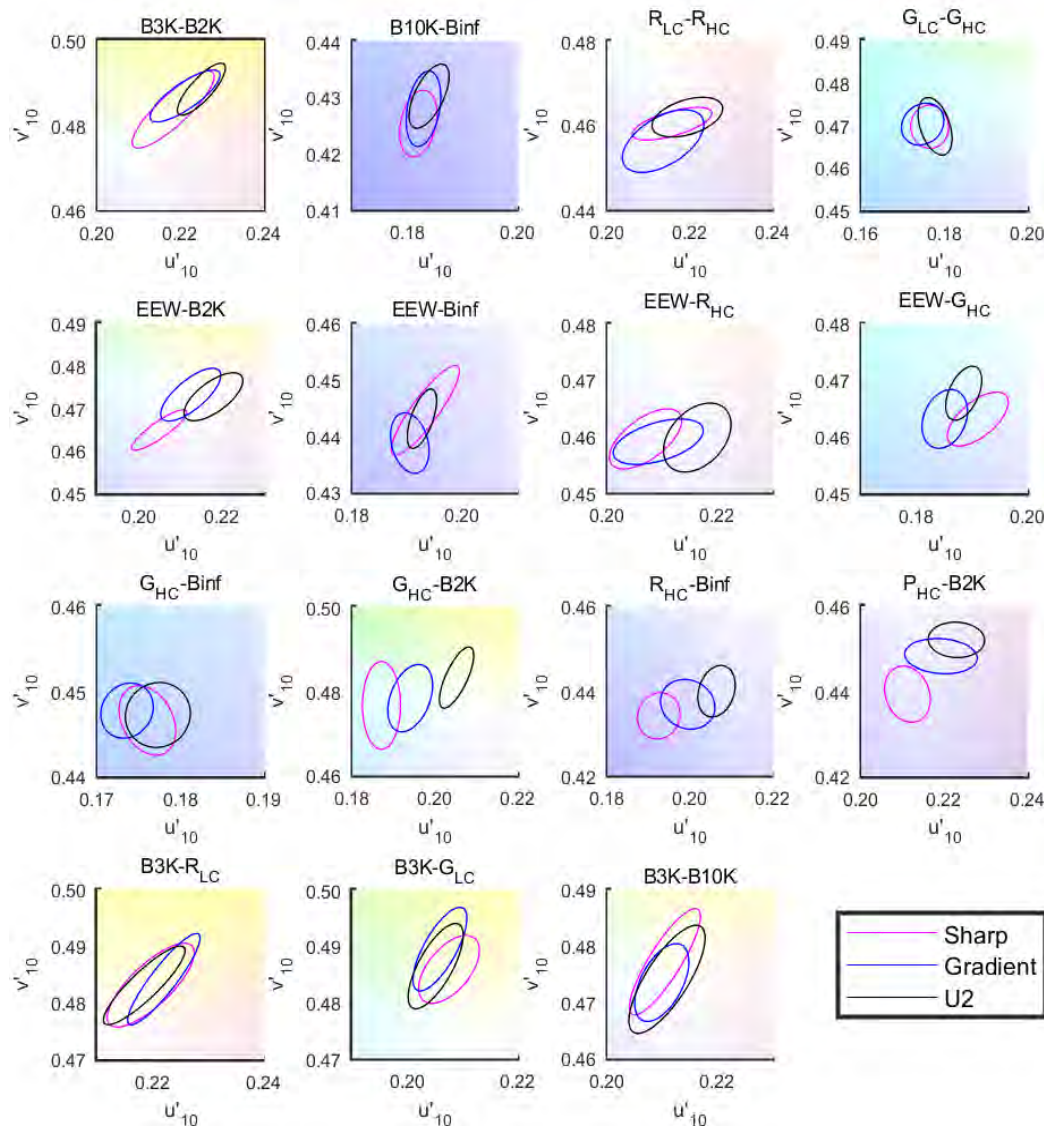
- Adapting field: 250 cd/m<sup>2</sup>, 80° FOV
- Fifteen illuminant color pairs
  - High-low chroma with the same hue (4 pairs)
  - EEW-high chroma (4 pairs)
  - High chroma pairs varying in hue (4 pairs)
  - Low chroma pairs varying in hue (4 pairs)
- Two transition types: gradient, sharp
- Each pair: three uniform illuminants
- Reference illuminant: EEW

### • Experiment:

- Target object: grey cube (6° FOV)
- Method: achromatic matching
- 10 observers



## ■ 3.2 matching results



### High-low chroma color pairs □

- Three spatial distributions (sharp, gradient, uniform) don't have significant difference in adaptation state.

### EEW-high chroma color pairs:

- Adaptation state under gradient transition is similar to that under uniform illumination with the same average chromaticity.
- For sharp transition, adaptation state is more influenced by EEW than the colorful one.

### High chroma color pairs (different hues):

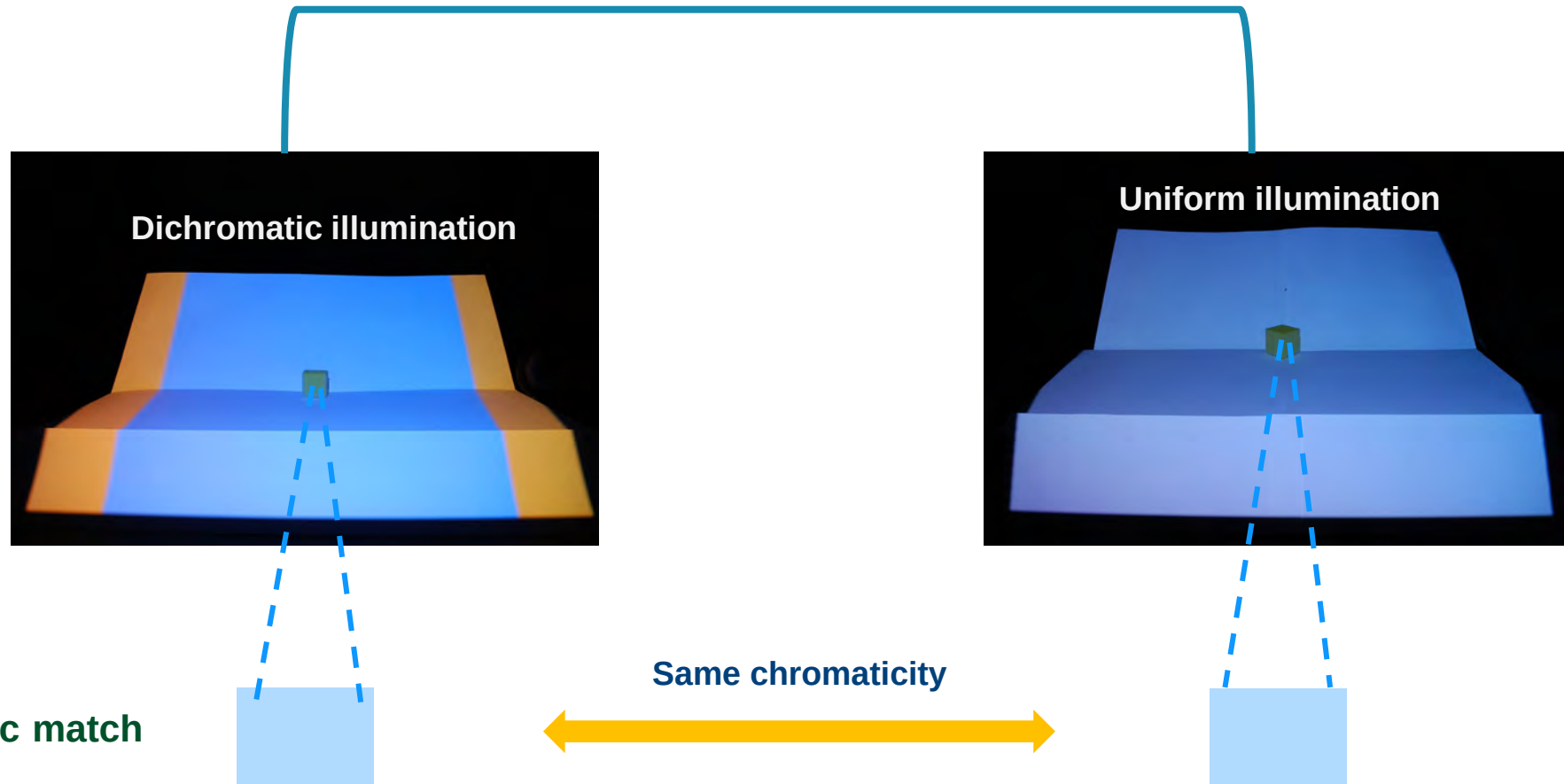
- Except Yellow-Green pair, similar adaptation state was achieved under gradient-transitioned dichromatic illuminant and uniform one.
- For sharp transition, the influence of yellowish illuminant (2000 K) is less than the other colorful one.

### Low chroma color pairs (different hues):

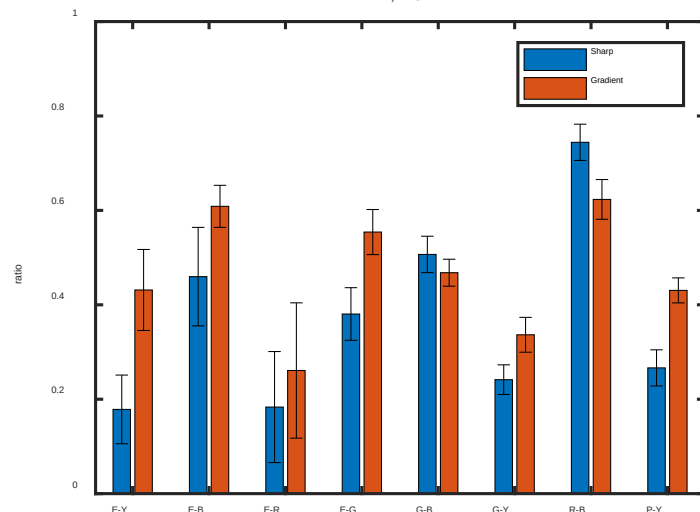
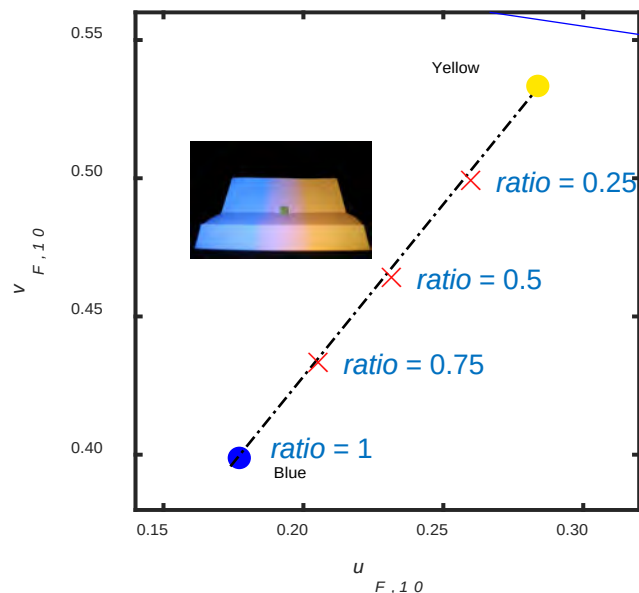
- Three spatial distributions (sharp, gradient, uniform) don't have significant difference in adaptation state.

### ■ 3.3 Equivalent illumination

Equivalent illumination  
(Experimental determined)



### 3.4 Equivalent illumination chromaticity



- General assumption:**

The equivalent illumination chromaticity (**EIC**) is located on the line connecting two illuminants.

$$uvY_{Equi} = ratio * uvY_{Yel} + (1 - ratio) * uvY_{Blue}$$

(ratio = 0 ~ 1)

- Grey world assumption:**

$$uvY_{Equi} = \overline{uvY_{adapt}}$$

- Gradient transition** □

The majority of conditions follow the grey world assumption.

- Sharp transition** □

EEW-high chroma pair □ ratio < 0.5

High chroma pair: depend on hue combinations

Biased by the illuminant more easily adapted to

## ■ 3.5 Modelling

Step 1: calculate the degree of adaptation ( $D$ ) ratio

$$ratio_D = \frac{D_{I2} / D_{I1}}{1 + D_{I2} / D_{I1}}$$

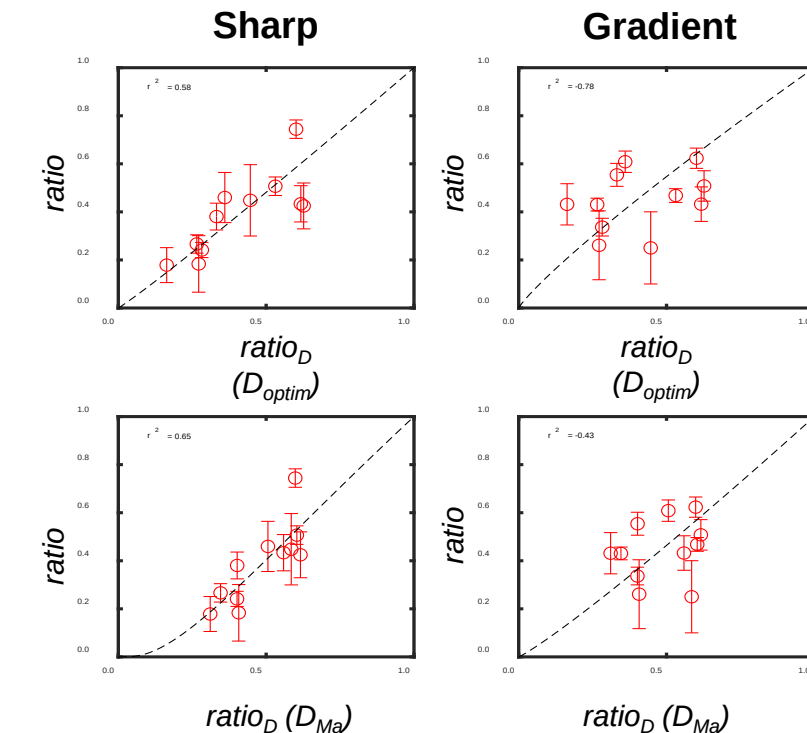
Step 2: calculate EIC quantified by  $ratio$  according to  $ratio_D$

$$ratio = \exp(-a \times (ratio_D)^b + a)$$

$$\begin{cases} ratio = \exp(-a \times (\frac{D_{I2} / D_{I1}}{1 + D_{I2} / D_{I1}})^b + a) & \text{Sharp transition} \\ ratio = 0.5 & \text{Gradient transition} \end{cases}$$

Step 3: calculate EIC under dichromatic illumination

$$\begin{pmatrix} X_{Equi} \\ Y_{Equi} \\ Z_{Equi} \end{pmatrix} = (1 - ratio) \begin{pmatrix} X_{I1} \\ Y_{I1} \\ Z_{I1} \end{pmatrix} + ratio \begin{pmatrix} X_{I2} \\ Y_{I2} \\ Z_{I2} \end{pmatrix}$$



Step 4: von Kries CAT

$$\begin{pmatrix} L_c \\ M_c \\ S_c \end{pmatrix} = \left[ D \begin{pmatrix} L_{rw} / L_{Equi} & & \\ & M_{rw} / M_{Equi} & \\ & & S_{rw} / S_{Equi} \end{pmatrix} + 1 - D \right] \begin{pmatrix} L \\ M \\ S \end{pmatrix}$$

|                             |          | $D_{\text{optim}} + EIC_{U1-U3}$ | $D_{\text{Ma}} + EIC_{U1-U3}$ | $D_{\text{Ma}} + EIC_M$ | $D_{\text{Ma}} + EIC_{\text{GW}}$ |
|-----------------------------|----------|----------------------------------|-------------------------------|-------------------------|-----------------------------------|
| High-low chroma             | Sharp    | 0.0033                           | 0.0053                        | 0.0065                  | 0.0078                            |
|                             | Gradient | 0.0042                           | 0.0066                        | 0.0084                  | 0.0084                            |
| EEW-high chroma             | Sharp    | 0.0017                           | 0.0037                        | 0.0034                  | 0.0114                            |
|                             | Gradient | 0.0016                           | 0.0047                        | 0.0058                  | 0.0060                            |
| High chroma (different hue) | Sharp    | 0.0041                           | 0.0062                        | 0.0085                  | 0.0150                            |
|                             | Gradient | 0.0023                           | 0.0049                        | 0.0081                  | 0.0092                            |
| Low chroma (different hue)  | Sharp    | 0.0045                           | 0.0086                        | 0.0070                  | 0.0119                            |
|                             | Gradient | 0.0061                           | 0.0096                        | 0.0135                  | 0.0119                            |

- Degree of adaptation model derived from single illumination condition is applicable for dichromatic illuminations
- No matter for sharp or gradient transition, the proposed EIC model ( $EIC_M$ ) performs quite well
- The proposed CAT model for dichromatic illuminations performs better than the one based on grey world assumption



Part 04

# Conclusion

## Conclusions

- The correlation between the stimulus and its surrounding scene under varying ambient lighting determines how the visual system adapts to the illumination color.
- For single illumination conditions, a new degree of adaptation model was developed by taking the size, chromaticity, luminance of the background, and the stimulus properties as the input variables.
- For dichromatic illumination, a model for estimating the equivalent chromaticity was proposed, which has been integrated in the von Kries CAT.

## Future work

- Verify the proposed model under more complex illumination conditions
- Propose a more comprehensive model for various viewing medium
- Explore the interaction between background color and illumination color



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# Thanks!

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